Pilot plant for processing flax fiber

Danny E. Akin [a,*], Roy B. Dodd [b], Jonn A. Foulk [c]

[a] *Russell Research Center, P.O. Box 5677, USDA-ARS, Athens, GA 30604, USA*
[b] *Department of Agricultural and Biological Engineering, Clemson University, Clemson, SC 29634, USA*
[c] *Cotton Quality Research Station, USDA-ARS, Clemson, SC 29633, USA*

Abstract

A flax fiber pilot plant is needed to process small samples of flax straw into fibers to facilitate research on retting and fiber properties. Our objective was to develop and test a modular design for a flax processing pilot plant based on a commercial line that was capable of cleaning fiber and seed flax straw from unretted, dew-retted, and enzyme-retted samples. The USDA Flax Fiber Pilot Plant (Flax-PP), which is the only research facility of this type in the United States, was designed according to the commercial 'Unified Line' (Czech Flax Machinery), but smaller and constructed in four individual modules. The modules and their order for processing were as follows: 9-roller calender, top shaker, scutching wheel, top shaker, 5-roller calender, and top shaker. Illustrations and diagrams of the operating modules are presented. Unretted 'Neche' linseed flax, dew-retted 'Natasja', and enzyme-retted 'Jordan' fiber flax were processed, and the cumulative weight loss of material at successive processing steps was determined to assess the effectiveness of cleaning. Fiber strength, fineness, and elongation were determined for the retted samples after cleaning through all the steps in the Flax-PP. A yield of fine fiber from the retted stems processed through the Flax-PP was acquired from further cleaning and refining by passage through a Shirley Analyzer. The various samples behaved differently at different stages of processing and the resulting fibers had different properties. The dew-retted Natasja fibers were stronger and finer than the enzyme-retted Jordan flax after pilot plant processing, but the Jordan fibers appeared cleaner and better retted. The Flax-PP effectively processed samples of diverse characteristics and will facilitate integrated research on retting methods for fibers with tailored properties.
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Keywords: Flax fiber; Retting; Cleaning; Properties; Flax; Pilot plant

1. Introduction

Flax (*Linum usitatissimum* L.) produces fibers in the outer regions of the stem between the outermost cuticle/epidermis tissue and the innermost woody, core cells (Van Sumere, 1992). The individual (i.e., ultimate) fibers are formed in bundles that encircle the core tissue. Flax, like other bast fiber plants, must undergo the process of retting to separate the fiber from the woody cells, which are termed shives and constitute the major trash component of flax fibers. Shives are detrimental to spinning efficiency and textile products. Furthermore, the cuticularized epidermis connects to fiber bundles, and poor retting leaves

* Corresponding author. Tel.: +1-706-546-3482;
fax: +1-706-546-3607.
E-mail address: deakin@qaru.ars.usda.gov (D.E. Akin).

large fragments of this material attached to fiber bundles, producing coarse fibers (Morrison et al., 1999). Stephens (1997) reported total fiber yields ranging from 20 to 30% of the straw in a series of flax varieties, where the majority of the non-fiber components is shives. Considerable effort must be expended to remove shives and other trash components from the fiber for industrial uses (Sultana, 1992).

Flax fiber has ready markets in a variety of industries, including textiles (as linen and blends with cotton and other fibers), composites, and specialty paper (Van Dam et al., 1994). Currently, interest is high in using natural fibers such as flax for glass fiber replacement in automotive parts (Lepsch and Horal, 1998). The advantages of natural fibers include their lower density, sound absorbance, and shatter properties lower than glass. Energy costs for producing composites with natural fibers have been reported to be about 80% less than glass fiber (http://www.daimlerchrysler.com).

Dew-retting, which is the method of choice currently for initially separating fiber and shives, has several disadvantages (Van Sumere, 1992). The search for a method to replace dew-retting has focused on enzyme-retting (Sharma and Van Sumere, 1992; Akin et al., 2000). Our research showed that fiber properties could be varied with different types of retting enzymes or with variation in the proportions of components in an enzyme-retting formulation (Akin et al., 2002; Evans et al., 2002). Furthermore, research indicated that the retting process must be integrated with subsequent mechanical processing steps to clean the fiber for specific applications. While preliminary work was done with hand-carding to process fibers (Akin et al., 2000), a search was begun to acquire a processing method with the following criteria: commercial in design and use, applicable with relative small samples of various types, and cost effective. The 'Unified Line' developed by Ceskomoravsky len, Humpolec, Czech Republic, met these criteria (Akin et al., 2001). Therefore, collaborative efforts by the US Department of Agriculture and Clemson University were begun to design and acquire modules for a pilot plant version of the 'Unified Line', which ultimately was delivered by Czech Flax Machinery, Měřín, Czech Republic. With the acquisition of these modules, a USDA Flax Fiber Pilot Plant (Flax-PP) for mechanical processing of flax was set up. Designing the components as free-standing modules gave flexibility in the order

and number of times each module would be employed in a cleaning cycle. Variable speed motors were installed to permit variability is direction and speed of the calenders in cleaning. Photographs, diagrams, and results from processed flax presented herein represent the first description and test data of the Flax-PP.

2. Material and methods

2.1. Cleaning modules

The pilot plant was set up as four separate modules representing several of the components that exist in a single line in commercial operations. Photographs and diagrammatic representations provide details of the modules (Figs. 1–4) that include a 9-roller calender, top shaker, scutching wheel, and 5-roller calender.

2.2. Samples

Three diverse flax samples were processed. 'Neche', a linseed variety, was grown in test plots at the Coastal Plains Experiment Station, Tifton, GA, as a winter crop in 2000/2001 and harvested on 24 May 2001. Plants were grown to full maturity and harvested with mature seed capsules. At harvest, plants were cut about 5 cm from the soil and stored indoors without weathering or retting until processed through the Flax-PP. One 4.5 kg sample was cleaned.

'Natasja' was grown in South Carolina as a winter crop in the mid-1990s to evaluate the growing, harvesting, and retting of flax. The flax was grown to maturity for seed, mowed, laid in swaths for dew-retting, and then baled and stored in a large round bale under cover. Three replicates of 4.5 kg each from one bale were tested.

'Jordan' fiber flax was grown as a winter crop in South Carolina and harvested in 2000 by drum mower before full maturity and optimally for fiber. The plants had weathered and slightly darkened before storage, indicating that some fungal colonization had occurred, but the plants were not retted. Plants were enzyme-retted according to a recently developed method (Akin et al., 2000) by soaking for 2 min (rather than spraying) crimped plants in a rotating barrel with 0.1% Viscozyme (Novozymes
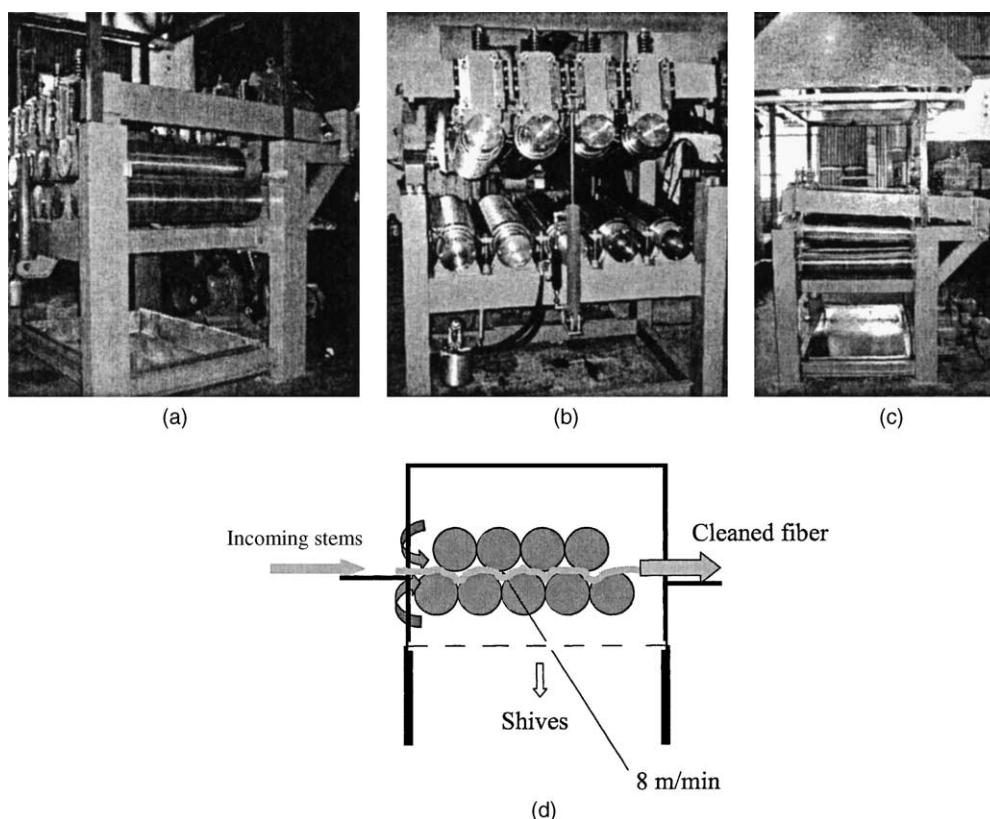
Fig. 1. Nine-roller calender for initial crushing and breaking of retted flax stems. Photographs showing (a) view of entry point for flax; (b) separation of top four (three grooved and one smooth) from five bottom rollers (two grooved and three smooth); (c) frontal view showing hood for dust collection; (d) diagram showing travel direction of stems and speed of material fiber through rollers to clean fiber. A spring force of 3920–4900 N is applied to each end of the top rollers.

North America, Inc, Franklinton, NC) plus 18 mM ethylenediaminetetraacetic acid (EDTA) as Mayoquest 200 (Callaway Chemical Co., Smyrna, GA). Plants soaked with enzyme formulation were incubated at 40 °C for 24 h and then washed twice. The retted plants were dried with turning and fluffing of the fiber mat to ensure uniform drying.

2.3. Fiber properties

Fine fiber yield was determined as the percent of the Flax-PP-cleaned fiber that was separated by the Shirley analyzer (SDL America, Charlottsville, NC, USA). Fiber strength in g/tex and percent elongation were determined by Stelometer (ASTM, 1999b). Fineness was determined by airflow using a modified cotton micronaire system (ASTM, 1999a) as described

(Akin et al., 1999) The modifications included a sample size of 5.0 g, and the largest shive fragments in the fibers were manually removed before testing. Fineness of flax in this manner had been correlated to a set of nine flax calibration grades obtained from the Institut Textile de France, Lille. Values for the various properties were evaluated for differences at $P < 0.05$ by analysis of variance.

3. Results

Four modules comprised the pilot plant for cleaning retted flax and were built under specifications of the commercial 'Unified Line'. In the commercial systems, similar components of the Unified Line for processing are set in a particular sequence (Zdenek
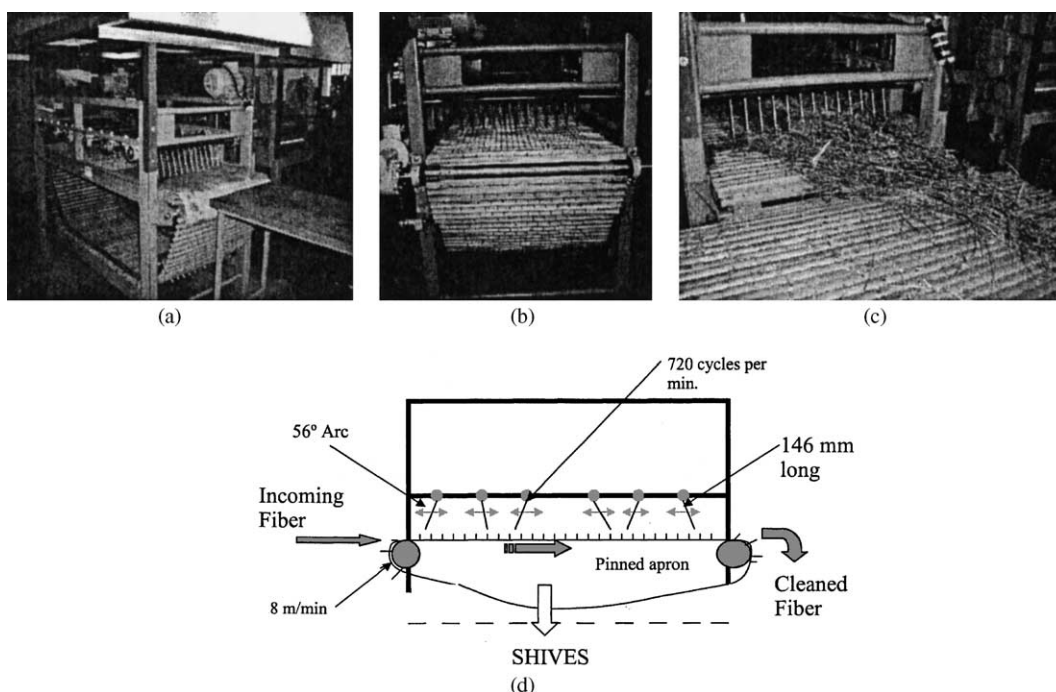
Fig. 2. Top shaker to remove shive from fiber. Photographs showing (a) side view; (b) frontal view showing metal prongs that vibrate to shake fiber as pinned apron moves fiber; (c) retted flax moving into top shaker; (d) diagram showing the speed, size, and action of prongs to clean the fiber and allow shives to fall underneath.

Sprynar, Czech Flax Machinery, s.r.o., Czech Republic, personal communication; Akin et al., 2001), and multiple units of one type may be included in the line. The major difference between commercial line and the pilot plant is in the width of the modules, with commercial units at 1200 mm and pilot plant units at 800 mm. By having modules rather than a single line, more flexibility is permitted, such as multiple runs through single components or changes in the processing sequence. During the first tests, multiple runs were evaluated on some modules. Flax straw and the processed fibers are manually distributed to the various modules during cleaning, whereas in the commercial systems the materials would be mechanically advanced to the next stage.

Flax is initially processed through the 9-roller calender, having maximum width of 1.74 m and length of 1.64 m (Fig. 1). Stems are crushed so that most of the shive, much of which has been separated from the fiber during retting, falls free from the fiber and is collected below the rollers. The configuration of the four

top (three grooved and one smooth) and five bottom rollers (two grooved and three smooth) are presented in Fig. 1, with Fig. 1b showing the separation of the two sets of rollers. A spring force of 3920–4900 N is applied to the end of the top rollers. The surface speed of the rollers was set at 8 m/min, but the inclusion of variable speed motors permits the roller speeds of each set to be independently controlled and varied.

The top shaker, with maximum width and length of 1.25 m × 2.26 m (Fig. 2a–c) employs a series of metal prongs that vibrate rapidly within the crushed and calendered fiber mat, which is pulled along with a pinned apron. The pins in the apron are about 23 mm long and vary from about 12 to 25 mm from the ends of the prongs as they arc back and forth over the mat. The distance between the wooden slats of the apron is about 45 mm, which is the opening through which the shives fall. The fibers are opened and aligned to some extent and freed from shive, which falls underneath the shaker through openings in the slats. The fibers are processed through the top shaker several times in
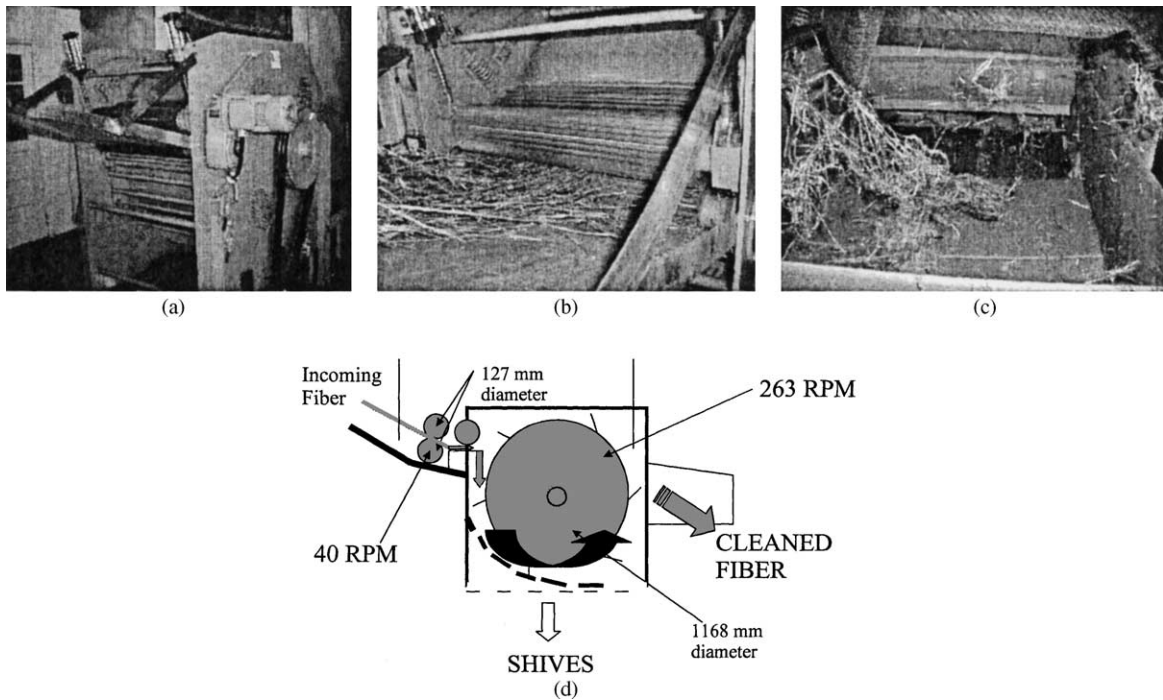
Fig. 3. Scutching wheel that strokes flax to shorten and clean fibers. Photographs showing: (a) scutching wheel in housing with roller plates in front; (b) flax entering roller plates; (c) flax collected after processing through the scutching wheel; (d) diagram showing the direction of fiber and the speed of feed roller and scutching wheel to clean the fiber and remove shives.

the cleaning cycle to mimic multiple top shakers for the commercial lines.

The scutching wheel, with maximum width and length of 1.64 m × 3.08 m (Fig. 3), which is enclosed within a metal housing, consists of a large wheel that transports the flax over the grid bars. A feed roller advances the fiber into the scutching wheel, which ro-

tates at 263 rpm and is the most aggressive module of the Flax-PP. The fibers are stroked over grid bars to separate fiber bundles and further remove shives. Fibers are opened and shortened, with fiber softness enhanced, during this stage.

The 5-roller calender, with maximum width and length of 2.0 m × 1.1 m (Fig. 4) has grooves on each
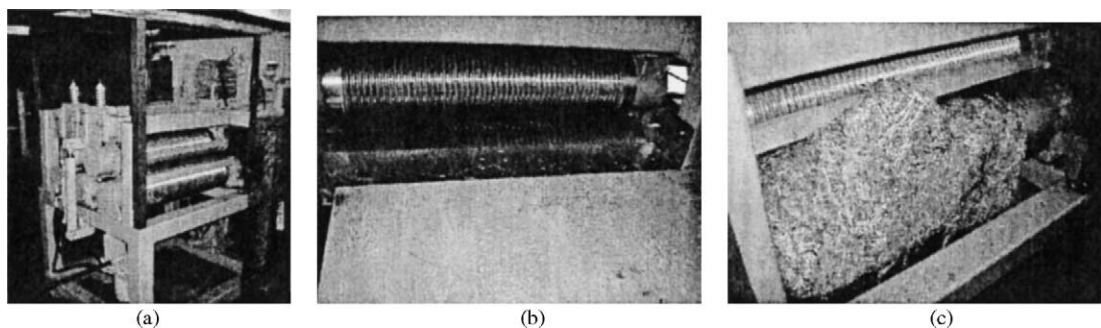

Fig. 4. Five-roller, grooved calender. Photographs showing: (a) side view; (b) frontal view of grooved rollers; (c) retted flax fiber mat exiting the rollers.

Table 1
Weight losses of flax material during each stage of cleaning through the USDA Flax Fiber Pilot Plant

Sample	Cumulative weight loss at successive processing stages (%)						Recovery (% of starting material)
	9-Roller crusher		Top shaker, 2×	Scutching wheel		Top shaker, 2×	
	1×	2×		1×	2×		
Neche-unretted[a]	40	50	45	72	75	71	29
Natasja DR-1[b]	14	25	63	69	71	76	24
Natasja DR-2[b]	21	30	65	69	71	76	24
Natasja DR-3[b]	5	21	60	65	65	69	31

[a] Linseed variety grown in 2000 to full seed maturity and stored inside without retting. Values are from one sample of 4.5 kg.
[b] Grown to full seed maturity in the 1990s and dew-retted in South Carolina, baled, and stored. Values are from three separate 4.5 kg replicates.

of the rollers to crush and mechanically stroke the fibers. Shives are further removed in this design. The fiber mat is compressed after the 5-roller calender. Fibers are finally processed again through the top shaker, which removes any remaining shive that was freed during the previous processes, but still remains in the fiber mat. This last step fluffs and opens the compressed mat and aligns the fiber mat to some extent.

The unretted linseed flax was processed to have a baseline of the worst case samples for comparison (Table 1). The 9-roller calender was very effective at crushing and removing shive, with weight loss (mostly due to shives) of 40%. A second run through this module of the unretted flax removed an additional 10%. For this sample, the top shaker was not effective, as a lack of retting permitted the shive to remain tightly bound to the fiber (the increase in weight is due to inadvertently collected non-fiber materials). Processing 1× through the scutching wheel removed considerable amounts of material, whereas a second run removed no more material. Processing twice through the top shaker also was ineffective in removing more material from this unretted sample (the increase in weight is due to inadvertently collected non-fiber materials). A final recovery of 29% (Table 1) represents processed fiber and considerable amounts of shives (Fig. 6), which still remained with the fiber after Flax-PP cleaning in this unretted sample.

Dew-retted flax stalks that were stored for several years processed very well through the Flax-PP modules. Three 4.5 kg samples were processed and the values kept separate to show sample variability (Table 1). The amount of shives removed by the first run though the 9-roller calender ranged from 5 to 21% of the starting weight, while a second run removed about 12% more material. The top shaker removed considerable amounts of material, as this material was loosened from the retted straw. As with the unretted flax, most of the material removed was shives. The scutching wheel was effective in removing non-fiber components but only to a small degree and with virtually no additional removal with a second run. Loosened shive was removed after processing through the 5-roller calender and cleaning twice through the top shaker. The final recovery of fiber averaged 26.3 ± 4% of the starting weight for the three replicates of dew-retted flax (Table 1).

Photographs of Jordan flax fiber processed at each module in the Flax-PP are shown in Fig. 5. Shive content and coarseness of fibers decreased through the subsequent processing stages. The assessment of Jordan was at slightly different conditions compared with the Neche and Natasja, and therefore results are shown in Table 2. Jordan, which had been weathered and then enzyme-retted, behaved differently during processing from the dew-retted Natasja sample. Processing once through the 9-roller calender gave results similar to the dew-retted sample (about 13% removed and consisting mostly of shives), but removal by the top shaker was considerably less with Jordan. The scutching wheel was effective in stripping away non-fiber materials, resulting in a cumulative loss of about half of the starting material. Successive processing through the top shaker, the 5-roller calender, and top shaker again removed only about 7–8% more material. Recovery was 45% of the initial weight and appeared to be fiber with most of the shives removed (Fig. 5).
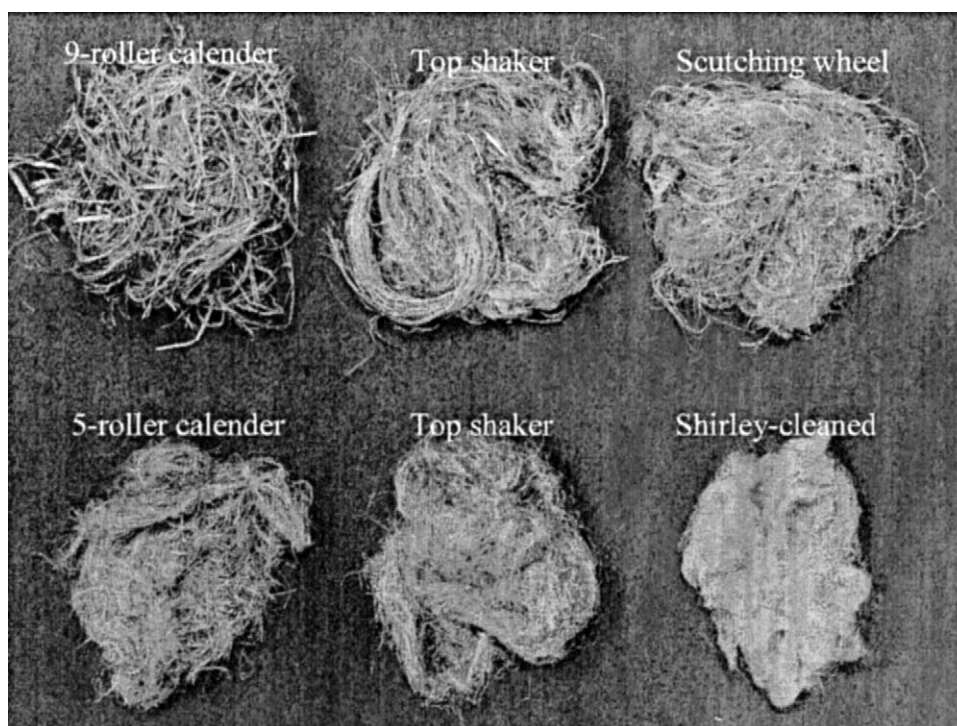
Fig. 5. Samples of enzyme-retted Jordan flax fiber after successive stages of Flax-PP processing. Flax is cleaned in an order beginning at the top left to bottom center. The sample at the bottom right is fiber subsequently cleaned by one pass through a Shirley analyzer to refine and shorten the fiber. The amount of shives and coarse fiber are reduced at successive stages of processing.

Samples examined with a stereomicrosope at 64× indicated variations in fiber coarseness and shive content in the various flax samples after Flax-PP cleaning (Fig. 6) The unretted sample particularly contained a considerable amount of shive along with coarse fibers. The dew-retted fibers, in contrast, were fine, but had some pieces of shive still remaining. The enzyme-retted sample appeared essentially shive-free.

Fiber properties for the two retted Flax-PP cleaned fiber samples substantiate that the materials were diverse (Table 3). Fibers from the dew-retted Natasja flax were stronger and finer (after removal of large pieces of shive) than the enzyme-retted Jordan after cleaning. Elongation, while statistically different, was low for both sample types. Overall, fine fiber yield, as determined by processing Flax-PP fibers through the

Table 2

Weight losses of flax material from enzyme-retted Jordan fiber flax at each stage of cleaning through the USDA Flax Fiber Pilot Plant[a]

Sample number	Cumulative weight loss at successive processing stages (%)							Recovery (% of starting material)
	9-Roller crusher, 1×	Top shaker, 1×	Scutching wheel, 1×	Top shaker, 1×	5-Roller calender, 1×	Top shaker		
						1×	2×	
1	12	39	46	51	52	54	55	45
2	14	42	48	53	53	54	55	45

[a] Jordan grown to optimize fiber quality, briefly weathered in the field and enzyme-retted by soaking in 0.1% (v/w) Viscozyme L (Novozymes, Franklinton, NC) + 18 mM EDTA (Callaway, Smyrna, GA).
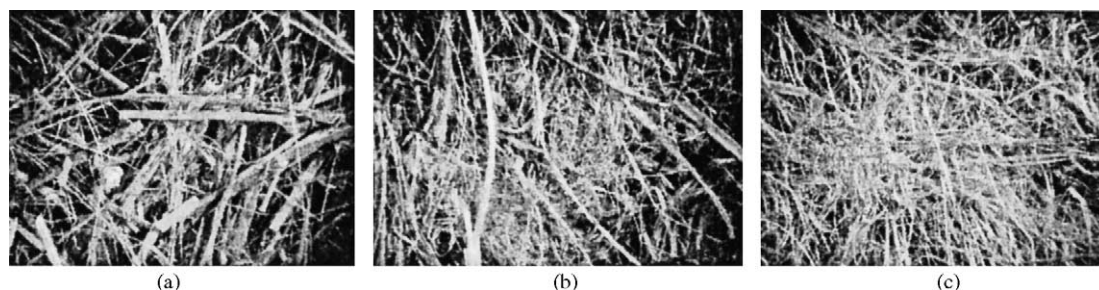
Fig. 6. Flax-PP cleaned flax fiber observed through a stereomicroscope at a magnification of $64\times$ showing various degrees of shive remaining. (a) Unretted Neche has considerable amounts of shive associated with coarser fiber. (b) Dew-retted Natasja has some large pieces of shive but fine fibers. (c) Enzyme-retted Jordan has less shive present than the other two samples.

Table 3
Properties of flax fiber after cleaning through the USDA Flax Fiber Pilot Plant

Sample	Strength[a] (g/tex)	Elongation[a] (%)	Fineness[b] (air flow)	Fine fiber yield[c] (%)
Dew-retted Natasja	40.1 ± 3.1 a	1.4 ± 0.1 a	5.3 ± 0.2 a	48
Enzyme-retted Jordan	25.0 ± 4.8 b	1.0 ± 0 b	$>8.0 \pm 0$ b	72

Values within columns with different letters (a, b) differ at $P = 0.05$ by the *t*-test..
[a] Average $\pm$ S.D. of three replicates, each consisting of six tests, by Stelometer.
[b] Average $\pm$ S.D. of three replicates, each consisting of four tests, by airflow.
[c] Percent by weight of fiber cleaned by the Shirley analyzer—one sample only.

Shirley Analyzer, was 48% for the Natasja and 72% for the Jordan samples.

4. Discussion

Traditional methods for cleaning flax fibers from retted straw include scutching and hackling to remove shive and non-fiber components (Ross, 1992; Sultana, 1992). Both the long line fiber, which consists of aligned fibers several cm long, and the tow fiber, which are short fibers removed from long fibers during scutching or hackling (ASTM, 2003), are produced by this method. The long line fiber is wet-spun on specialized equipment for high-value linen textiles. Tow fibers can be refined, carded, and used for blending with cotton or other fibers and dry spun for textiles or used in composites or geo-textiles. Alternatively, processing methods have been described to collect an "all-fiber" or total fiber product from flax, where the fiber is not processed for long line and tow (Sultana, 1992). Utilizing total flax fiber may improve overall properties over tow fibers, which are often weak and short. Current interest in bio-based materials for numerous applications has led to renewed interest for equipment to produce total fiber from flax stems. Such processes would decorticate the bast plants and produce non-aligned, non uniform fibers for uses other than long line for linen. Fibers could then be obtained from various sources where obtaining long line fiber for linen is not possible or even desired. For example, large resources of straw produced as waste product of the linseed industry, e.g., greater than a million Mg annually from western Canada (Domier, 1997), could supply fiber for composites, blending with other fibers in textiles, and other non-linen uses. Use of linseed straw, e.g., from North Dakota and Canada, harvested without the specialized equipment for long line fibers could provide a low-cost source of material for diverse applications (Foulk et al., 2002).

The four modules comprising the Flax-PP were built under specifications of the commercial 'Unified Line'. One such commercial 'Unified Line' is being established in Kingstree, SC for processing flax fiber from a variety of sources. In these commercial systems, cleaning components of the 'Unified Line' are set in a particular sequence (Akin et al., 2001). The Flax-PP lacks some components that may be included in the

commercial line, such as a bottom shaker and conveyors that allow shives to fall underneath. With these essential modules for the Flax-PP rather than a single line, costs can be reduced and more flexibility is possible for research goals, such as multiple runs through single components or changes in the processing sequence. By having material fed in lots into the Flax-PP rather than as a continuous feed as in commercial systems, some differences can occur in yield and outcome. The Flax-PP, however, was as efficient as the commercial systems in removing shives and producing usable fibers from diverse flax stems.

In this initial description of processing with the Flax-PP modules, we did not intend to define reasons for the differences, but rather tried to show the cleaning pattern of vastly different flax straw material. The flax straw that was evaluated differed in several factors, including cultivar, type of retting, pre-processing treatment, and storage. The properties of the fibers collected after Flax-PP processing differed, further indicating the diversity in these samples. While it is not possible to attribute different behavior to any single factor (such as retting), general differences among the samples, however, were evident. For all samples, the greatest loss of material, which appeared to be essentially all shive, occurred with the 9-roller calender and the first pass through the top shaker. For the intact, unretted stems, about 40–50% of the material was removed with just the 9-roller calender. The top shaker was ineffective in removing more material, whereas the aggressive scutching wheel did remove more material. For the two retted samples, shive was separated from fiber in the retting process and was subsequently lost during transport of samples. The proportion of fiber, therefore, was greater in the starting material in retted than with unretted flax. Nonetheless, the unretted stems were processed and provided fiber, although visually showing considerably more residual shive material and coarse fibers than the retted samples.

The enzyme-retted sample had been crimped prior to retting as a standard step to facilitate enzyme penetration within the stem (Akin et al., 2000). This step shortens the shive in addition to rupturing the stem integrity. During and after enzyme-retting, the flax is manipulated through several turning and tumbling steps, which further facilitates the separation of the crimped shive from the fiber. The lower amount of shives removed after the first treatment with the top shaker and

the higher amount of fiber at the end of processing suggest that shive content was lower in the starting material than the dew-retted sample. Flax-PP cleaned fiber had about $5\times$ more shives in the dew-retted than the enzyme-retted samples (about 27% versus 6% shive) as determined by the near-infra-red spectroscopy technique to measure shive content in flax (Barton et al., 2002; Song, Barton, Morrison, and Akin, unpublished data). The greater yield of fine fiber after Shirley cleaning further suggests that this enzyme-retted flax sample was better retted in terms of more fine fiber and less trash.

Retting is a major influence on the yield and quality of flax fibers for textiles and composites (Van Sumere, 1992; Van de Weyenber et al., 2003). It is clear, however, that mechanical processing alters fiber properties, and the retting and cleaning processes must be integrated to tailor fibers with specific properties and applications. The Flax-PP effectively cleaned a variety of flax samples with different behavior at individual modules for different samples. While fiber could be produced even with unretted flax, our results confirmed the importance of retting on fiber quality. The structure for housing the pilot plant is unconditioned so that humidity and temperature were not controlled in these studies. Samples that felt moist because of high humidity did not process well, and further work should address proper conditioning for optimal processing. Fibers produced by commercial or pilot plant versions of the 'Unified Line' are able to produce total fiber that is non-aligned and non-uniform in length. For some applications, this material is ready to use. Where cleaner, more refined fibers are required, additional processing is required. Work is in progress to include an additional cleaning and carding system to the Flax-PP for larger amounts of refined (cottonized) fibers with the goal of testing fibers with a broader range of properties.

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